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Matera Laser Collocation Experiment

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27 May 1987

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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FOR THE COMMANDER

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MATERA LASER COLLOCATION EXPERIMENT

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ABSTRACT

Three laser ranging stations were collocated at Matera, Italy, in January, February, and March 1986. They observed 92 passes of the LAGEOS Satellite, of which 56 passes were observed by more than one system. This set of data allows intercomparison of the three laser ranging systems, and assessment of the Quick Look data from each system. In addition, this data set allows examination of tropospheric refraction models using dispersion since two distinct optical wavelengths were used. It has been found that the three laser ranging systems agree to within 1.7 cm in range. It has also been found that the nominal (Marini and Murray, 1973) refraction model has no significant errors greater than 0.12 cm in Zenith refraction and 0.64 cm in the mapping function down to 20° elevation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

MATERA LASER COLLOCATION EXPERIMENT

I. INTRODUCTION

Satellite Tracking Laser Ranging (SLR) systems have continuously improved in accuracy and data volume since the first successful satellite track in 1966. Many systems have been developed using similar but different designs and procedures for calibration and operation. The functional design objective is to provide data with an accuracy of approximately 1 cm for support of geophysical investigations. SLR data have many uses, most of which hinge on computation of precision satellite trajectories. Even though many ingenious methods of calibration have been devised, a side by side comparison is another unique method of verifying the accuracy of these systems. Such an intercomparison obviously does not establish absolute accuracy. However, if two systems, each with their own calibration methods, agree to within the expected accuracy, one can claim with some degree of confidence that they both have that accuracy. The collocation of three SLR systems at Matera, Italy in the first quarter of the calendar year 1986, has provided a set of data for such an analysis. The target of this investigation is the LAGEOS satellite, which has an orbital accuracy of 10 cm.

There are four parts to this analysis. The first is the computation of normal points from data with different error statistics and sampling rates. Normal points have become common in the analysis of satellite laser data for a number of reasons. They allow us to reduce the number of raw observations in the already complex orbit computation, and combine observations from systems with different data rates and accuracies. In this investigation, normal points also allow direct comparison of the three systems. This is because, in general, range observations are not made at the same time. Normal points, on the other hand, can be given at prescribed times.

The second part of this analysis is the comparison of the final reduced data from the three systems. Here we do a side by side comparison of the different systems to determine how well they agree with each other. The third part is the comparison of the final full rate data with the Quick Look (QL) data. QL data are available in near real time from the tracking systems and are used for a number of objectives that depend on accuracy. The accuracy of the QL data can be determined by comparison with the final full rate data. Finally, the fourth part of this analysis is the investigation of the tropospheric refraction model. The SLR systems used different optical wavelengths. The small, but finite dispersion of the troposphere, mandates careful treatment of the refraction. This is, of course, necessary to intercompare the satellite range data. However, the dual frequency data allows us to directly measure the refraction.

II. NORMAL POINT COMPUTATION

The idea of normal points is simply to reduce the number of raw observations to be comparable to the amount of information contained in these observations. This concept is difficult to quantify in a rigorous manner, in part because of the axiom that one man's signal is another man's noise. It is not clear how much information is actually contained in an oversampled pass. Nevertheless, it is clear that the thousands of observations in a single satellite pass, which are not necessarily distributed uniformly, contain a considerable amount of redundant information. In other words, the observations are highly correlated. In addition, these observations contain information concerning random data errors which are of no interest in our analysis, and should be removed if possible.

To reduce the number of raw observations, we used metric range/time combinations as our framework for normal point computation. We are not in a position to justify this technique as it probably does not lead to an efficient, complete, and robust mapping of the data. Perhaps another technique should have been used. We can only point out that our method for the normal point computation seems to work.

The computation of normal points proceeds in two steps (see Figure 1). The first step uses a crude orbit model of the LAGEOS orbit. The orbital model is a precessing Keplerian ellipse. This model is used to remove the large variation in observed range, by an iterated least squares fit of all the observations to the predicted range. Four fit parameters are chosen: a time offset, dt, and the three station coordinates, dX, dY, dZ. This is called a station navigation. The formal observation equations are:

$$r\,(\mathrm{obs}) - r\,(\mathrm{com}) = \begin{array}{c} \bar{r} \cdot \bar{v}\,dt \\ -\,(X\cos\theta + Y\sin\theta)\,dX \\ +\,(X\sin\theta - Y\sin\theta)\,dY \\ -\,Z\,dZ \end{array}$$

where X,Y,Z are the geocentric cartesian coordinates of the observing site, θ is the sidereal angle, $\bar{r}$ and $\bar{v}$ are the position and velocity vectors of the satellite. On each iteration the station coordinates are changed by dX, dY, and dZ. The mean anomaly of the orbital elements (M) is also changed by

$$dM = 360 * n * dt/86400 \text{ (deg)}$$

where n is the mean motion in revolutions per day, and dt is in seconds.

During the fit, gross observation errors are rejected. For LAGEOS, using an orbit model including zonal harmonics J2, J3, and J4, this fit results in residuals of the order of 100 m. These residuals, of course, are very smooth, as illustrated in Figure 2.

The residuals from step one are then used as data in a second step, which uses a spline polynomial fit to these data. The spline is a least squares cubic spline fit[1] with breakpoints spaced

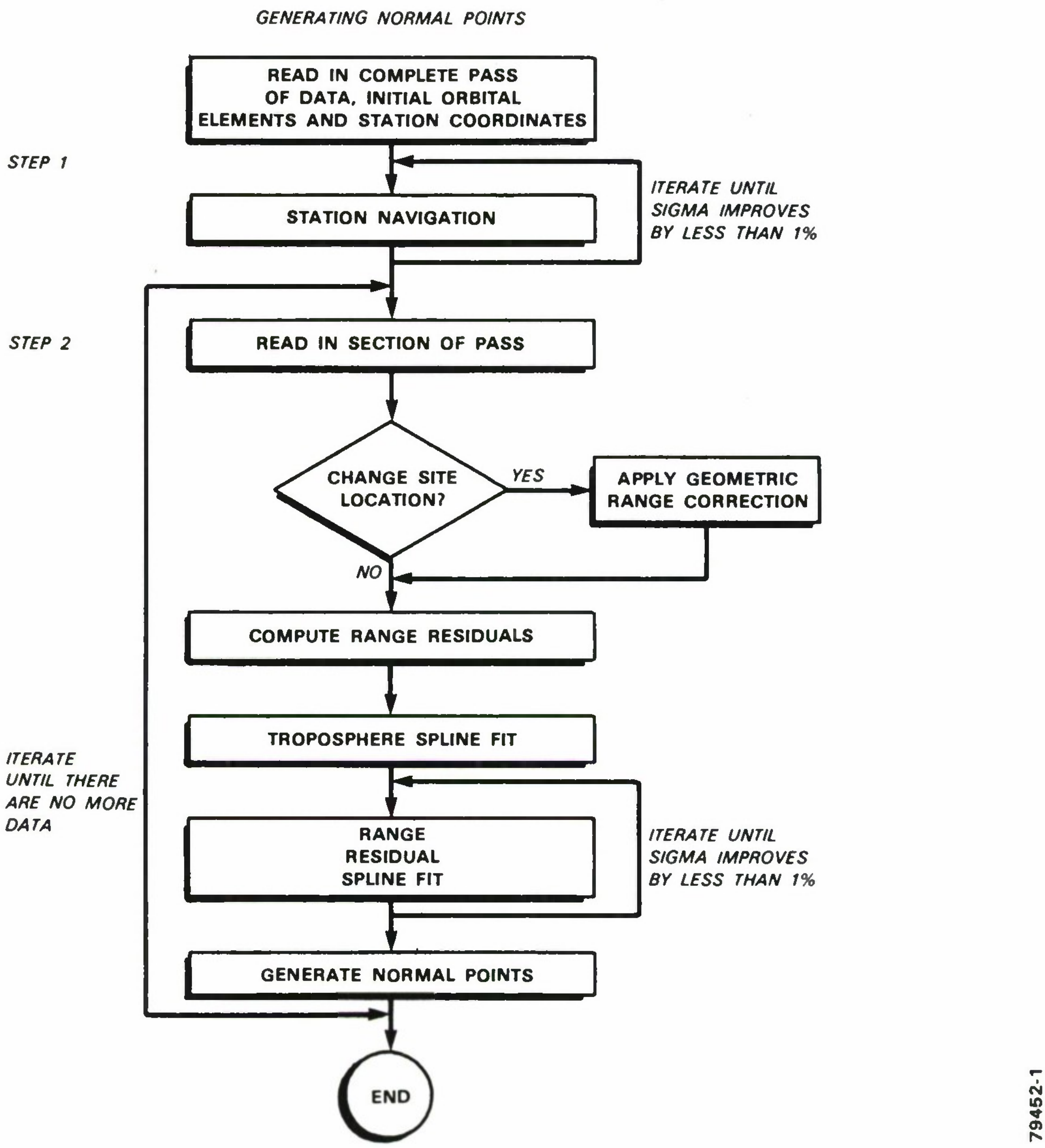

Figure 1. Flowchart of normal point computation.

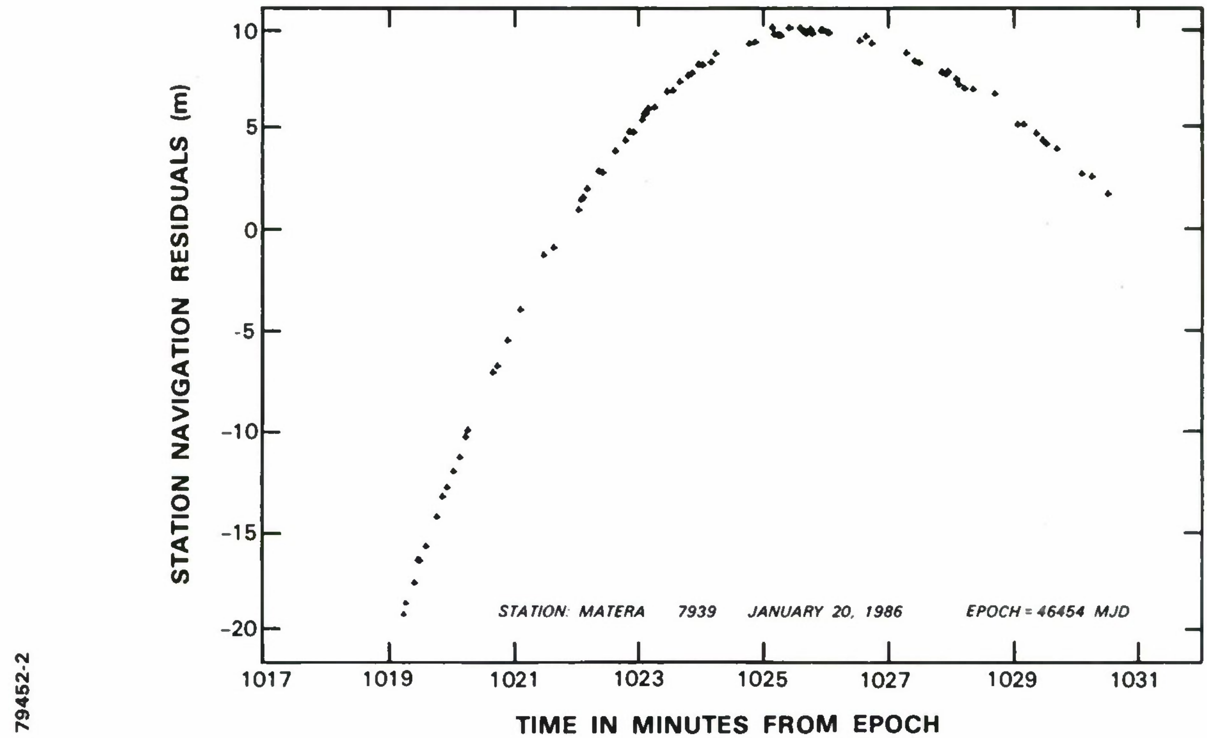

Figure 2. Plot of station navigation residuals vs time.

every minute. All our spline fits used single knots, which implies that all the derivatives of the spline function must be continuous at the breakpoints. We found that the spline fit was not well-behaved on intervals with very little data. Therefore, each pass is processed in segments, separated by gaps of 1 min. or longer where the number of raw observations was less than 4 per min. Hence, a whole pass without significant data gaps could possibly be treated in one fit. The knots were arbitrarily chosen on each whole minute. The spline fit is iterated to screen bad data using a three-sigma rejection criterion. All the data points in the fit were given equal weight. Each spline fit is summarized by an rms of the observation residuals, which is then used to estimate the accuracy of the normal point computed from the spline coefficients. Table I is a sample of the spline fit results, and Figure 3 shows the residuals of this fit.

The Matera normal points are generated by evaluating the spline at the midpoint of each knot space, i.e., at each half minute. The spline value is then added to the orbit model which is evaluated for the same time, including the station navigation and Mean Anomaly correction, to obtain a normal point at the given time.

The normal points for the MTLRS1 and MTLRS2 sites were computed in a similar fashion. This computation, however, requires an additional step. In order to make the system intercomparison, the MTLRS data must be reduced to the Matera site. Before the station navigation is

TABLE I Statistics for Matera Range Residual Spline Fit				
Interval	**Mean cm**	**RMS cm**	**Accepted Points**	**Rejected Points**
1	3.1	17.8	6	0
2	-1.4	9.7	8	0
3	5.0	20.0	5	0
4	-6.4	16.3	7	0
5	1.2	11.2	11	0
6	.2	10.5	7	0
7	3.0	17.3	8	0
8	-4.9	7.8	9	0
9	3.8	11.8	5	1
10	-3.4	13.4	7	0
11	2.7	20.7	6	1
12	1.6	10.8	4	0
For Segment	.0	14.6	83	2
*** Spline fit to the first 12 minutes of pass 34.				

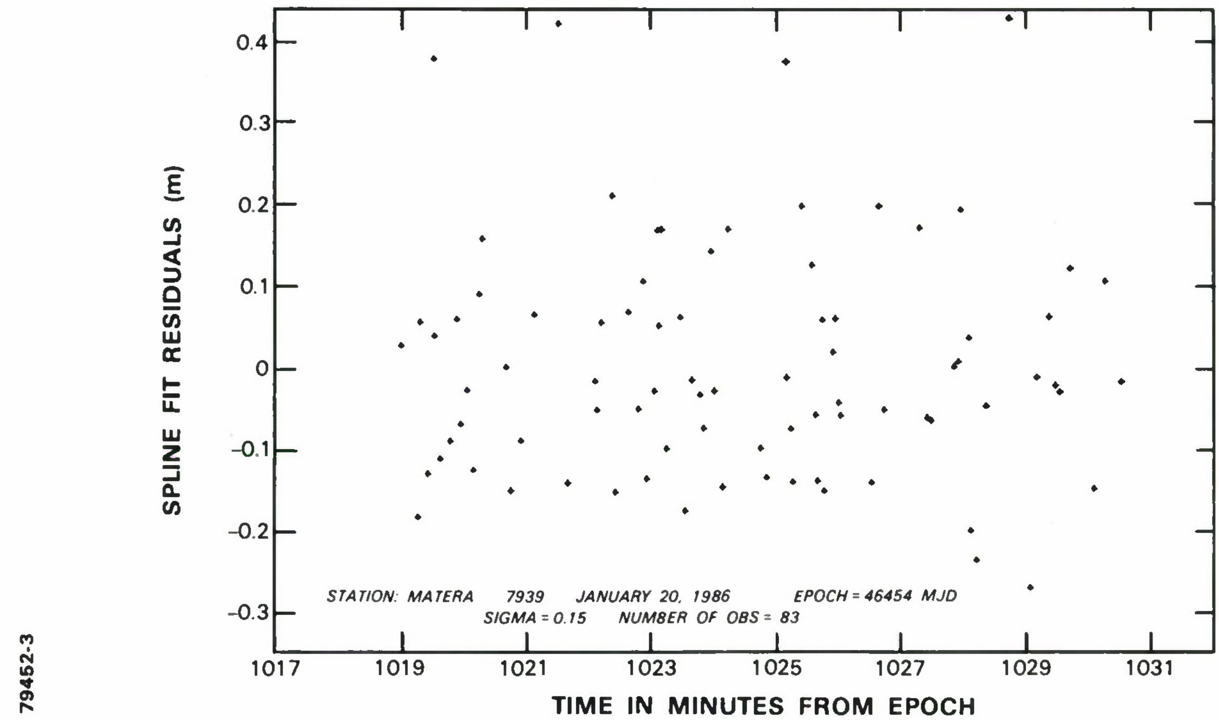

Figure 3. Plot of spline fit residuals vs time.

performed, the MTLRS raw observations are transformed to the Matera site using a geometric correction which is described in detail in Section IV of this report. The transformed raw observations are then fit to the same orbit computed for the Matera data. Using this fit, the station navigation residuals for the MTLRS data are obtained. As with the Matera residuals, a least squares cubic spline is fit to the residuals with a knot spacing of 1 min. Again, the spline fit is iterated using a three-sigma screening criterion. The normal points are generated by evaluating the spline and adding the orbit model, including station navigation, at the prescribed times. This process provides, *inter alia*, normal points for each sensor, at identical times.

The refraction correction was treated in a similar way. A cubic spline fit was made to the refraction data with the same knot spacing and evaluated at the time of each normal point to be passed along with the "observed" normal point. The refraction was a smooth analytical function without random errors. Therefore, iteration of the spline fit was unnecessary.

An uncertainty, or weight, is associated with each normal point. This uncertainty is obtained from the standard error of the spline fit in the knot interval divided by root of n-1, where n is the number of data points within the knot space interval containing the normal point. However, if the uncertainty computed in this way is less than 2 cm, then a value of 2 cm is given.

III. QUICK LOOK DATA COMPARISON

The Quick Look (QL) data are generally available within a few hours of the pass in the format given in Appendix A, and are used for a number of applications where accuracy is important. The QL data are a sampling, or subset, of the data, and so a direct comparison is relatively easy, and the QL data points can be directly compared with the final full rate data. Differences can occur for a number of reasons, for example:

(1) Refined treatment of calibration data

(2) Final time correction to UTC

(3) Recalibration of troposphere data through calibration of instruments or removal of measurement or recording errors

(4) Transmission errors or reformatting errors.

These issues are not trivial as evidenced by the fact that there were six "final" sets of data distributed, each with slight revisions to the preprocessing of the "raw" data.

The 168 passes obtained from the collocation experiment were compared. Eight of the original Quick Look passes were not included in the final data distribution, and twenty of the final data sets did not correspond to any Quick Look data. These anomalous passes were probably a result of transmission errors, leading to mistagging of station, day or year.

Of the 140 passes where a match of QL and full rate data was possible, the common ranges were compared with the results shown in Table II. Also given in Table II are the mean difference and the rms about the mean, and the number of points rejected. Here the rejection criterion was set at 10 m, and served to eliminate only gross errors. For several passes from Matera (7939), the mean difference exceeded 30 cm. This was due to a data management problem at some point in the data path of the QL data. The calibration of 7939 uses a precisely surveyed remote target. Before and after each pass ranges to the target are made, and the difference from the survey is used to set the system calibration. This observed range includes the tropospheric refraction delay which should be removed before computing the system calibration. For those passes, with QL and full rate data differences of 30 cm or greater, this correction was not made. This data management problem was identified at the time and should no longer exist in the QL data. The MTLRS1 and MTLRS2 systems use an internal calibration, and this data management problem does not occur.

The overall agreement of the QL and full rate data for Matera has an agreement of about 2 cm rms, excluding the >30 cm calibration refraction errors. This difference is assumed to result from refinement of the calibration data. For MTLRS the difference of QL and full rate was essentially zero. However, a small number of passes had larger errors. We assume these outliers are due to transmission errors. For both Matera and MTLRS data more complete screening would certainly further reduce the difference between QL and full rate data. The overall agreement of the QL and full rate measurement data is summarized in Table III. Of course, the measurement errors, noise etc., are common to both QL and full rate data, and so this is not a measure of the accuracy of the system. For that we turn to the next section.

The refraction data also had small revisions. However, these had no effect on the results of this comparison as the comparison was made between the raw range observations.

TABLE II(a)

Comparison of Quick Look Versus Full Rate Data (Matera)

Pass No.	MJD	Mean cm	RMS cm	Accepted Points	Rejected Points
2	46440.770	2	0	144	4
4	46441.050	0	0	58	0
6	46442.942	3	0	160	0
7	46443.093	0	0	160	0
8	46443.745	2	0	160	0
9	46443.886	2	0	160	0
11	46444.026	2	0	158	7
13	46444.690	2	0	156	0
14	46444.831	0	0	160	0
15	46444.970	1	0	153	0
16	46445.121	1	0	18	1
17	46445.798	1	0	109	0
18	46445.917	1	0	91	0
19	46446.061	1	0	159	1
20	46447.002	3	0	160	0
21	46447.156	-1	0	34	0
22	46447.668	2	0	159	0
23	46447.811	3	0	160	0
24	46447.947	1	0	160	0
25	46448.097	0	4	160	0
27	46449.840	-4	0	160	0
28	46449.979	3	0	155	0
33	46450.925	4	0	160	0
34	46451.071	1	0	160	0
36	46452.691	-2	0	40	0
38	46453.765	2	0	320	0
39	46453.903	1	0	318	0
41	46454.708	2	0	320	0
42	46454.849	1	0	320	0
43	46454.994	5	0	60	0

TABLE II(a) (Continued)					
Pass No.	MJD	Mean cm	RMS cm	Accepted Points	Rejected Points
46	46458.775	-2	0	158	0
47	46458.913	2	0	160	0
48	46459.068	-2	0	320	0
50	46465.682	3	0	160	0
51	46465.954	2	0	40	0
55	46469.079	2	0	160	0
57	46471.771	2	0	130	0
58	46471.909	2	0	160	0
59	46472.058	4	0	160	0
61	46473.806	1	0	110	0
63	46474.749	2	0	47	0
64	46474.886	2	0	33	0
65	46477.862	0	0	290	0
66	46478.004	3	0	160	0
68	46480.702	3	0	160	0
69	46480.844	-1	0	160	0
70	46480.984	-2	0	8	0
71	46481.787	4	0	160	0
74	46482.733	1	0	278	0
75	46482.873	1	0	312	0
76	46484.901	1	12	312	8
77	46485.052	2	0	160	0
79	46485.850	31	0	159	0
81	46487.884	35	0	159	0
82	46491.966	0	0	31	0
84	46494.785	4	0	160	0
85	46494.921	2	0	160	0
86	46495.078	2	0	160	0
87	46498.990	32	0	89	0
90	46501.826	28	0	160	0
91	46501.970	23	0	155	1
92	46503.061	33	0	138	0

TABLE II(b)

Comparison of Quick Look Versus Full Rate Data (MTLRS1)

Pass No.	MJD	Mean cm	RMS cm	Accepted Points	Rejected Points
13	46444.711	0	2	195	5
17	46445.791	0	1	129	2
23	46447.827	0	1	136	1
28	46449.982	0	2	194	6
34	46453.769	-4	53	394	6
39	46453.907	0	1	390	10
41	46454.735	0	1	136	6
42	46454.852	4	51	392	8
49	46464.582	0	1	150	12
50	46465.673	0	2	182	18
51	46465.976	0	1	82	1
52	46468.652	0	7	390	10
53	46468.796	0	1	197	3
54	46468.931	0	1	191	9
56	46471.627	0	1	195	5
57	46471.776	0	1	192	8
58	46471.910	-1	7	194	6
59	46472.079	0	1	33	3
66	46478.011	-3	37	194	6
67	46480.573	0	1	60	2
68	46480.706	0	1	197	3
69	46480.843	0	1	192	4
82	46491.951	0	1	194	6
83	46494.647	0	1	30	3
84	46494.789	0	1	196	4
85	46494.924	0	1	196	4
89	46501.560	1	1	48	3
90	46501.827	1	1	196	4
91	46501.968	0	1	192	8

TABLE II(c) Comparison of Quick Look Versus Full Rate Data (MTLRS2)					
Pass No.	MJD	Mean cm	RMS cm	Accepted Points	Rejected Points
8	46443.608	0	1	196	4
10	46443.899	0	1	195	5
11	46444.029	0	1	199	1
13	46444.693	-5	63	190	7
14	46444.836	0	1	194	6
15	46444.972	0	1	194	6
17	46445.788	0	1	44	4
18	46445.932	0	0	27	3
19	46446.076	0	1	197	3
20	46447.018	-19	111	36	164
22	46447.678	-1	7	192	8
23	46447.816	0	1	185	15
24	46447.953	0	1	191	9
27	46449.842	0	1	162	8
28	46449.985	0	1	118	6
30	46450.133	0	1	75	5
35	46451.606	0	1	65	11
36	46452.688	0	0	50	8
37	46453.642	0	1	328	10
38	46453.779	-1	1	368	24
39	46453.906	7	65	392	8
40	46454.587	0	1	30	12
41	46454.715	0	1	386	14
42	46454.859	11	138	90	4
43	46454.994	0	1	62	2
45	46458.634	0	1	82	9
46	46458.779	0	1	198	2
47	46458.915	-1	62	194	6
48	46459.061	0	1	384	16

TABLE II(c) (Continued)					
Pass No.	MJD	Mean cm	RMS cm	Accepted Points	Rejected Points
49	46464.584	0	1	15	1
51	46465.959	0	1	194	6
56	46471.632	0	1	51	1
58	46471.914	0	1	197	3
59	46472.064	2	73	188	8
61	46473.807	0	1	50	1
62	46473.940	0	1	197	3
63	46474.749	−1	10	105	6
64	46474.884	3	35	192	8
70	46481.003	0	1	193	7
71	46481.803	0	1	83	4
72	46481.933	0	1	196	4
75	46482.875	0	1	278	4
77	46485.060	0	1	73	1
78	46485.572	0	1	191	9
79	46485.858	0	1	197	3
81	46487.890	0	1	194	6
84	46494.791	0	1	16	0
87	46498.993	0	1	54	4
89	46501.557	0	1	230	22

TABLE III Quick Look Versus Full Rate Overall Agreement			
Site	Weighted Mean cm	Weighted RMS cm	Accepted Points
Matera	3.95	.45	9701
Matera*	1.40	.50	8841
MTLRS1	−.10	10.36	5467
MTLRS2	.28	12.00	7918
*omitting passes with mean greater than 20 cm.			

IV. SYSTEM INTERCOMPARISON

The normal point computation provides observations at prescribed times with some reduction of random errors. Therefore, while the noise of the raw Matera (7939) data approaches 20 cm, it is possible to generate normal points that have a much reduced noise level. The full rate data were provided in the format given in Appendix B, and the normal points were computed as described above and corrected for refraction. The MTLRS data were transformed to the Matera site as described below.

To transform the MTLRS data to the Matera site, we added a geometric correction, dr, to each MTLRS raw observation (range). The correction in range is computed from:

$$dr = \cos(El) \sin(Az)\, DX + \cos(El) \cos(Az)\, DY + \sin(El)\, DZ$$

where

DX = -17.321 m DY = -34.376 m DZ = -5.889 m	for MTLRS1, and
DX = -33.834 m DY = -36.263 m DZ = -6.113 m	for MTLRS2.

DX, DY and DZ define the vector from an MTLRS laser to the Matera laser. These values were supplied by survey data of the Matera site. El and Az are the elevation and azimuth to the satellite as seen from Matera. To obtain these values, a database was set up containing the azimuth, elevation and time data from the Matera full rate data records. For each pass of MTLRS data, we fit a spline to the Matera elevation and azimuth data in the MTLRS time frame. The time frame encompassed the time of the MTLRS pass plus or minus 1 h. We used a least squares cubic spline with 5 min. knot spacing for these fits. The azimuth and elevation splines were evaluated at the time of each MTLRS raw observation. Next, the correction dr was calculated and added to the raw range observation. Then, the normal point calculation proceeded as for the Matera normal points.

For each pass, we computed the difference between the Matera and the MTLRS1 normal points, the Matera and the MTLRS2 normal points, and the MTLRS1 and MTLRS2 normal points. The weighted mean difference, rms, and standard error of unit weight are given for each pass in Table IV (a, b, c). The uncertainties as described in the computation of normal points were used to compute the weights. The weight for each range difference wi was obtained from the weight of each normal point w1 and w2 by combining as variances:

wi**2 = w1**2 + w2**2.

TABLE IV(a)

Normal Point Range Comparison (Matera-MTLRS1)

Pass	Weighted Mean cm	Sigma cm	Sigma Bar	Number of Points
13*	1.2	4.4	1.089	14
15*	1.1	4.8	.942	5
17*	2.9	3.8	.499	3
23*	1.8	5.8	1.541	6
28*	-3.6	7.1	1.543	14
38*	2.3	5.8	1.280	30
39*	-.9	6.4	1.291	35
42*	-2.1	3.0	.769	19
50	-2.0	11.3	1.669	19
53	-3.7	6.8	1.020	4
57	2.5	9.2	1.981	8
58*	.9	5.0	.921	36
62*	4.0	11.2	1.418	3
66	2.8	5.4	1.313	35
68	3.2	4.0	.859	27
69	-3.3	4.8	.966	23
84*	-1.0	4.7	.990	12
85*	-15.6	110.3	24.359	9
90	-2.1	2.8	.693	22
91	-5.2	10.7	1.676	9
Total	-.01	19.10		333

* included in original 16 passes.

TABLE IV(b)

Normal Point Range Comparison (Matera-MTLRS2)

Pass	Weighted Mean cm	Sigma cm	Sigma Bar	Number of Points
2	9.4	4.7	.977	10
7	3.1	3.5	1.088	2
9	.7	4.8	1.158	26
10	-.6	3.3	.873	12
11	-7.9	153.2	41.237	34
13*	-.6	5.5	.931	19
14	.0	4.7	1.035	20
15*	4.9	11.8	2.721	16
22	2.8	8.6	1.040	10
23*	-.2	6.6	1.395	14
24	2.7	3.5	1.047	32
28*	-.5	13.5	2.605	21
29	2.1	9.7	2.333	19
33	1.5	3.5	.800	35
38*	.6	5.7	1.280	13
39*	-.3	3.7	1.000	20
41*	4.8	6.5	1.059	17
42*	-3.3	5.1	1.082	4
43	15.7	109.8	22.654	6
44	6.0	88.3	25.892	18
46	1.5	7.8	1.463	16
47	-1.2	7.2	1.334	32
48	.2	3.5	.894	30
51*	-6.0	—	—	1
58*	.1	6.1	1.121	22
59	-1.6	3.5	.772	19
62*	1.6	2.5	.310	5
70	-5.3	2.9	.787	5
71	2.0	8.3	2.046	5
75	2.8	8.0	1.810	8
79	-9.3	3.1	.743	8
81	1.8	4.4	.549	5
85*	-79.9	130.1	28.125	12
88	-14.0	—	—	1
Total	.38	48.92		515

* included in original 16 passes.

TABLE IV(c) Normal Point Range Comparison (MTLRS1-MTLRS2)				
Pass	**Weighted Mean cm**	**Sigma cm**	**Sigma Bar**	**Number of Points**
15*	.8	1.3	.459	4
23*	-.4	1.5	.528	5
28*	.9	1.5	.535	10
38*	-.2	1.7	.615	14
39*	-1.2	1.4	.455	20
42*	-3.8	2.4	.786	4
58*	-1.0	2.0	.715	22
62*	-3.0	—	—	1
64*	-3.9	.8	.256	3
85*	-1.9	35.0	12.366	12
Total	-1.33	12.60		94

* included in original 16 passes.

The standard error of unit weight, sigma bar, is close to unity for Matera-MTLRS indicating that, in a statistical sense, the individual error estimates for Matera are consistent. For MTLRS1-MTLRS2 the standard error of unit weight is roughly 0.6 indicating the error estimates for MTLRS are conservative. Recall that the minimum weight allowed was 2 cm. From this, one could conclude that in a statistical sense the error in MTLRS should be 2 * 0.6/root(2) = 0.8 cm!

From this set of individual pass biases, one can determine the average difference in absolute calibration. One has at least two choices: (1) straight average of the means, and (2) weighted average using the standard error of unit weight. In the first case, some 3-sigma data screening is necessary with the results given in Table V. In general, the points with large sigma bar are screened out. In the second case, no screening is needed with the results given in Table V. Table V also gives the results obtained by NASA (private communication) for their analysis of the collocation data.

It is clear that the calibration results depend on the weighting used. We believe the statistical weighting is more correct. The differences from the two weighting philosophies indicate that the true uncertainty of the result, i.e., the true MTLRS1-MTLRS2 bias is equally likely to be -1.33 or -0.83 cm.

TABLE V Normal Point Intercomparison Results (All Passes)				
Unweighted Means				
Lasers	**Mean Difference cm**	**Weighted Sigma cm**	**Number of Passes**	**Number of Normal Points**
Matera-MTLRS1	0.01	5.67	16	324
Matera-MTLRS2	0.75	5.86	30	447
MTLRS1-MTLRS2	-0.83	1.65	9	83
Weighted Means				
Lasers	**Weighted Mean cm**	**RMS cm**	**Number of Passes**	**Number of Normal Points**
Matera-MTLRS1	.01	19.10	20	333
Matera-MTLRS2	.38	48.92	32	515
MTLRS1-MTLRS2	-1.33	12.60	9	94
Lasers	**Weighted Mean cm**	**Weighted Uncertainty cm**	**Number of Passes**	**Number of Normal Points**
Matera-MTLRS1	.20	1.80	16	N/A
Matera-MTLRS2	.50	1.60	25	N/A
MTLRS1-MTLRS2	-1.30	.50	7	N/A

It is also clear that, though the Matera, MTLRS1 and MTLRS2 systems agree in absolute range to 0.01, 0.38 and -1.33 cm, respectively, these results are inconsistent. They say that Matera and MTLRS1 have essentially no systematic difference, yet that MTLRS2 is shorter than Matera by 0.38 cm and longer than MTLRS1 by 1.33 cm. This discrepancy arises because the two data sets have very little overlap. It indicates that the three systems agree in calibration to about 1.7 cm. We get virtually the same result from the first, unweighted average, of the normal point differences. Furthermore, since the standard error of unit weight is close to 1.0, it indicates that, in a statistical sense, the individual error estimates are consistent. This validates the system accuracy as well as the integrity of the normal point calculation.

V. TROPOSPHERIC REFRACTION MODEL EVALUATION

This analysis of data from the Matera collocation experiment allows us the opportunity to evaluate the tropospheric model used to correct the data. This evaluation is important for two reasons. First, it enables us to check that the model was consistently implemented in all phases of the laser data analysis. Small systematic errors in the refraction model need not have recognizable signatures and can be masked by other effects. Second, it gives us an estimate of how accurate the tropospheric model is. We would like some confirmation that the model is valid as refraction errors cannot be separated from some calibration errors. For example, a signal strength (range) dependent calibration error could mask into an elevation dependent refraction error. The first concern was investigated by a comparison of the refraction correction provided on the final full rate data with the one calculated using the meteorological data from the QL data. The two values of the correction were in complete agreement. The second concern was investigated by observing the frequency dependence of the troposphere dispersion.

We were able to observe the frequency dependence of the tropospheric refraction because the data were collected at two different optical wavelengths, 0.693 μm (red-Matera) and 0.574 μm (green-MTLRS1 and MTLRS2). The Marini and Murray[2] tropospheric model was used to compute the estimated tropospheric range correction at these two wavelengths. This is the model that NASA uses in its data reduction. It was the only model in our survey of refraction models that included a term for the frequency dispersion of the troposphere. Our survey included the Marini and Murray model, the present tropospheric model used at the Millstone radar site[3] and the Davis mapping function[4] combined with the Saastamoinen formula for the tropospheric Zenith correction.[5] The majority of tropospheric models were designed for microwave radio frequencies. The models designed for microwave frequencies were limited to wavelengths where there is no tropospheric frequency dispersion.

It is interesting to compare the models surveyed. Although we can not directly compare the Zenith refraction estimates because the models were designed for different frequencies (the Marini and Murray model for optical, and the Davis and Millstone models for microwave), we can compare their mapping functions. The Marini-Murray tropospheric correction is given by the following expression:

$$\Delta R = \frac{f(\lambda)}{f(\phi,H)} * \frac{A + B}{\sin E + \dfrac{B/(A+B)}{\sin E + 0.01}}$$

where

$$A = 0.002357\ P_o + 0.000141\ e_o$$

$$B = (1.084 \times 10^{-8})\ P_o T_o K + (4.734 \times 10^{-8})\ \frac{P_o^2}{T_o} * \frac{2}{3 - 1/K}$$

$$K = 1.163 - 0.00968 \cos(2\phi) - 0.00104\ T_o + 0.00001435 * P_o$$

$$f(\lambda) = 0.9650 + 0.0164/\lambda^2 + 0.000228/\lambda^4$$

$$f(\phi,H) = 1.0 - 0.0026 \cos(2\phi) - 0.00031\ H$$

P_o = Atmospheric pressure at the laser/radar site (millibars)

T_o = Atmospheric temperature at the laser/radar site (Kelvin)

e_o = Water vapor pressure at the laser/radar site (millibars)

ϕ = Latitude

H = Height above sea level (km)

E = Elevation angle

λ = Wavelength of radiation (μm)

The Marini-Murray Zenith refraction correction can be approximated by:

$$\Delta R\ (\mathrm{ZENITH}) = \frac{f(\lambda)}{f(\phi,H)} * (A + B)$$

and their mapping function ZMM(E) can be approximated by:

$$\mathrm{ZMM}(E) = \cfrac{1.0}{\sin E + \cfrac{B/(A+B)}{\sin E + 0.01}} \quad .$$

The Millstone mapping function ZMH(E) is defined by:

$$\mathrm{ZMH}(E) = \frac{1.0}{\sin E + 10^{-3} * \mathrm{CTN}\ E} \quad ,$$

and the Davis mapping function ZD(E) is defined by:

$$\mathrm{ZD}(E) = \cfrac{1.0}{\sin E + \cfrac{AD}{\tan E + \cfrac{BD}{\sin E + CD}}} \quad ,$$

where

$$\begin{aligned} AD = 0.001185\ [1.0 &+ 0.6071 \times 10^{-4} (P_o - 1000) \\ &- 0.1471 \times 10^{-3}\ e_o \\ &+ 0.3072 \times 10^{-2} (Tc - 20) \\ &+ 0.1965 \times 10^{-1} (B_o + 6.5) \\ &- 0.5645 \times 10^{-2} (HT - 11.231)]\ , \end{aligned}$$

$$
\begin{aligned}
BD = 0.001144\ [&1.0 + 0.1164 \times 10^{-4}\ (P_0 - 1000) \\
&+ 0.2795 \times 10^{-3}\ e_0 \\
&+ 0.3109 - 10^{-2}\ (Tc - 20) \\
&+ 0.3038 \times 10^{-1}\ (B_0 + 6.5) \\
&- 0.1217 \times 10^{-1}\ (HT - 11.231)]\ ,
\end{aligned}
$$

$CD = -0.0090$,

B_0 = Tropospheric temperature lapse rate (K/km),

HT = Height of the tropopause (km),

Tc = Surface temperature in Celsius, and
P_0 and e_0 as above.

B_0, the tropospheric temperature lapse rate, was set at $-5.6 * 10^{-3}$ (K/km), and HT, the height of the tropopause was set at 13.6 km. Both of these are typical values of the above parameters.

The mapping function itself is dimensionless. The difference in the mapping functions can be converted to units of centimeters by assuming a standard Zenith refraction value of 2.1 m. In Figures 4 and 5, we see the differences in the mapping functions of the three models plotted as a function of elevation: The Millstone — Marini-Murray values; the Davis — Marini-Murray values; and the Marini-Murray — Marini-Murray values. Figure 4 shows the differences between

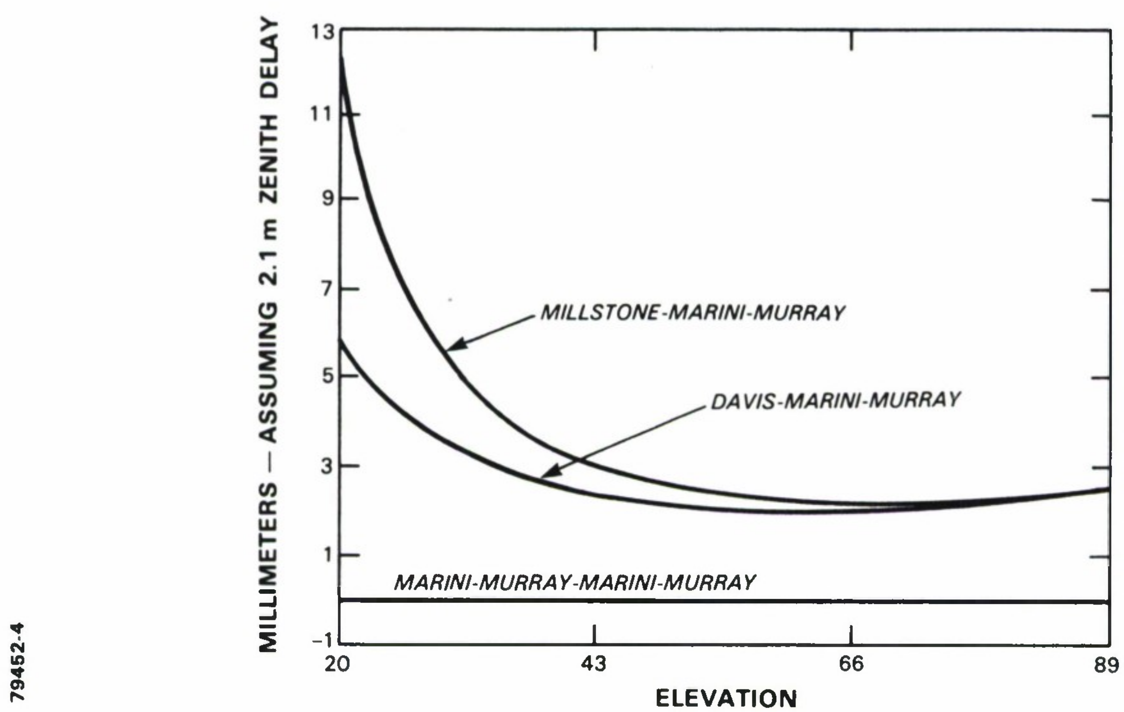

Figure 4. Mapping function comparison (20 to 90°).

20 and 90° of elevation while Figure 5 shows the differences on an expanded scale from 5 to 90° of elevation. Note, that the Marini-Murray mapping function does not predict a value of 1.0 at 90° elevation. Also, note that at 20° the difference between the Millstone and the Marini-Murray models is 1.2 cm, whereas the difference between the Davis and the Marini-Murray models is 0.6 cm. This comparison allows us to better judge the results of our study.

The difference in the tropospheric correction evaluated by the Marini-Murray model at 0.574 and 0.693 μm is small. At 90° elevation, the estimated size of the refraction correction for Matera is approximately 2.24 m, while for the MTLRS systems it is about 2.30 m, resulting in a difference of 6 cm. At 20° elevation, and typical meteorological conditions the estimated size of the refraction correction for Matera is 6.49 m, while for MTLRS systems it is 6.65 m, resulting in a difference of 16 cm.

We can evaluate how well the model is predicting the tropospheric correction by computing the difference between the uncorrected normal point ranges (ranges adjusted to the Matera site) and subtracting from this the difference between the modeled tropospheric range corrections: i.e.,

$$\text{delta} = R^*_m - R^*_{1,2} - [\Delta R_m - \Delta R_{1,2}],$$

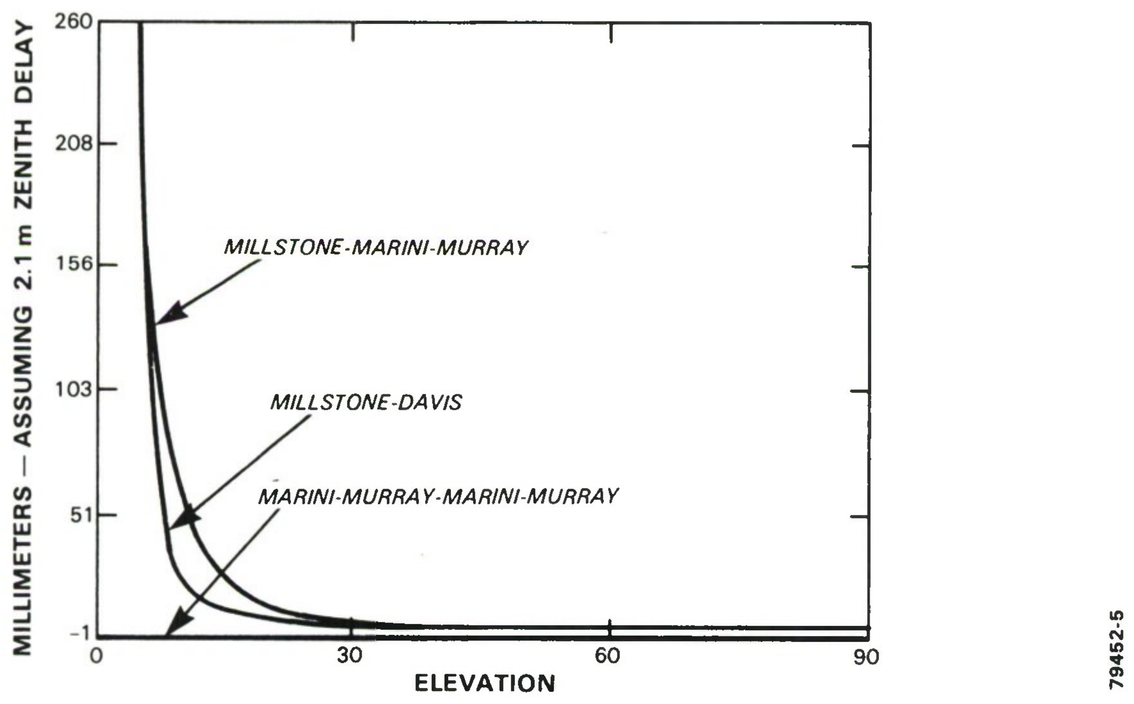

Figure 5. Mapping function comparison (5 to 90°).

where

R^*_m = the Matera normal point range,

$R^*_{1,2}$ = the normal point range from MTLRS1 or MTLRS2

ΔR_m = the modeled tropospheric refraction correction at the Matera site

$\Delta R_{1,2}$ = the modeled tropospheric refraction correction at MTLRS1 or MTLRS2

The only difference between the uncorrected normal point ranges for the three sites should be the difference between the respective values for the tropospheric range correction, the value we refer to as delta. In practice, the refraction correction for each station was calculated using the meteorological data from that station. The actual small differences in measured pressure, temperature, and water vapor pressure also contribute to the values of delta. If we were to convert the difference between the measured ranges to a value for the tropospheric range correction at one of the wavelengths, we would find that a 1.0 cm error in the difference in the ranges amounts to an approximate 40 cm of error in the estimate of the range refraction. Therefore, one cannot use this data to directly calculate the refraction. Nevertheless, by comparing the deltas (the difference between the modeled values for the tropospheric refraction subtracted from the difference between the two uncorrected ranges), and averaging over the entire data set, one can investigate systematic errors in the model.

Our analysis involved calculating deltas for all of the passes which had data from more than one site, excluding data sets that only had MTLRS1 and MTLRS2 data since these systems were both using the same wavelength. The deltas were collected into a single data file and were sorted by elevation. The weighted mean and root mean square of the entire data set were computed. The data were then grouped into bins of 10° elevation, i.e., 0 to 10, 10 to 20, 20 to 30°, and so on. Within each bin, a weighted mean was computed and the standard deviation of the mean of this data subgroup was calculated, enabling us to estimate uncertainty of the mean. The entire data set was screened using a 3-sigma criterion.

Figures 6, 7, and 8 all have the same format. The mean and root mean square of the entire data set is given in the upper right hand corner of the graph. The mean is also plotted as a straight line in each graph. The mean and the corresponding error bars for each data bin of 10° of elevation are also plotted. The statistics for each data bin are printed in the bottom right hand corner of each graph. Figure 6 shows the data from the Matera and MTLRS1 sites; Figure 7 shows the data from Matera and MTLRS2; and Figure 6 shows the combined data sets of Figures 6 and 7.

The tropospheric refraction component can be divided into two separate components, a Zenith refraction correction and a mapping function which is approximately 1.0/sin (elevation). If there was an error in the measurement of the Zenith correction, it would be amplified by the mapping function at the lower elevation. However, the 20 to 30° bin in Figure 8 has a mean of 0.34 ± 0.64 cm, or in other words not significantly different from zero. This data bin also has a significant number of data points (88) so that we have some confidence in the statistics. Therefore, if we consider that the mean for the 20 to 30° bin is 0.34 ± 0.64 cm (see Figure 8), we can assume that the Zenith tropospheric correction that was applied is correct to within 0.34 * sin (20°), or to within 1.2 mm. In addition, since there is no evidence of error in the 20 to 30° data bin, we can say that the mapping function of the Marini-Murray model is valid down to 20° to ± 0.64 cm.

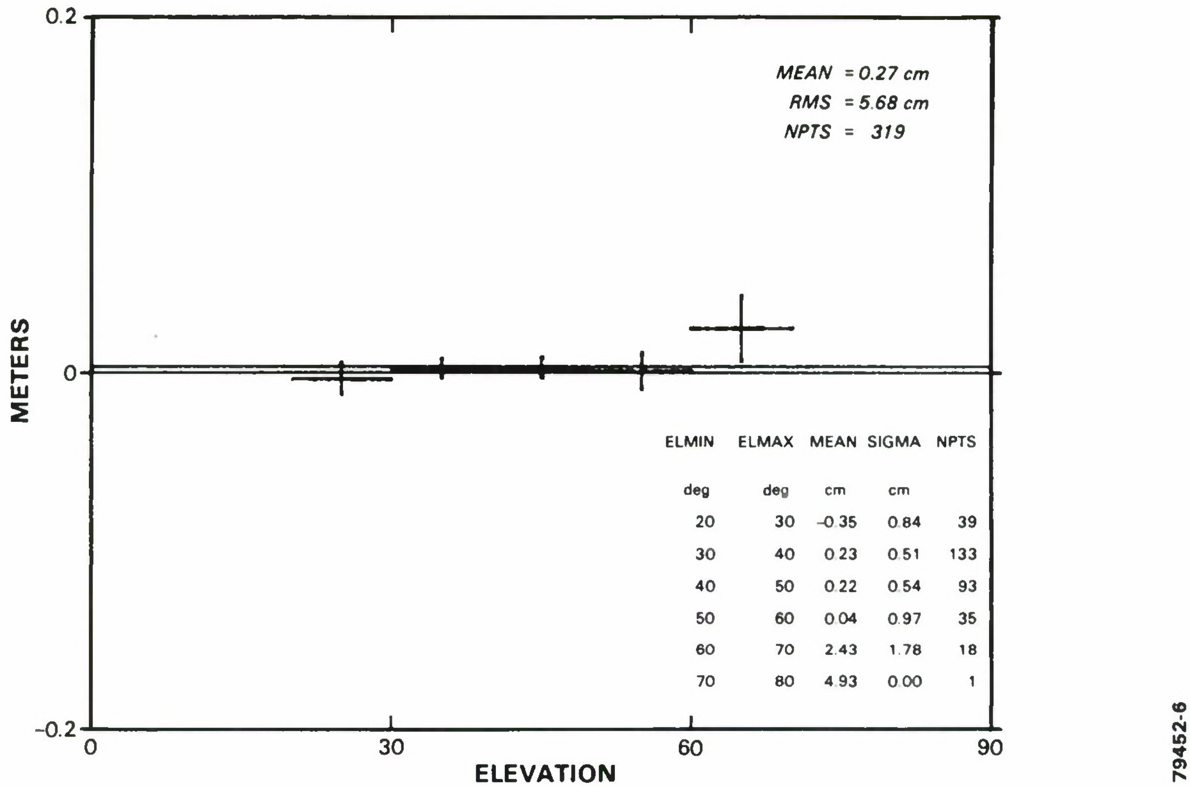

Figure 6. Matera — MTLRS1 tropospheric correction evaluation.

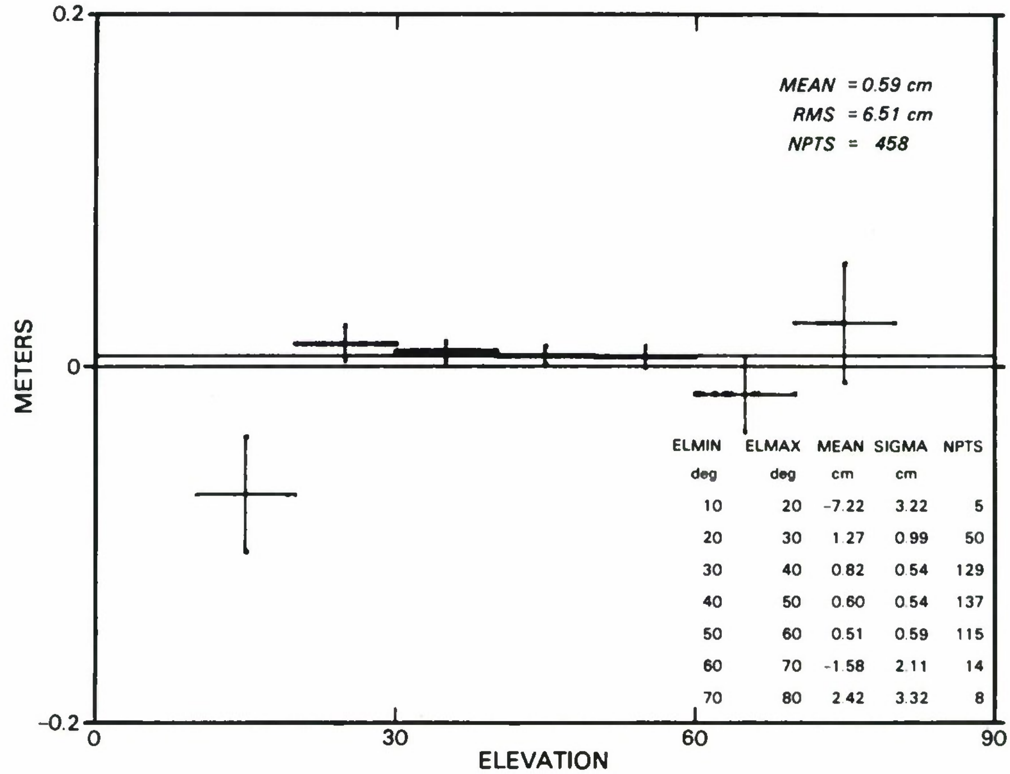

Figure 7. Matera — MTLRS2 tropospheric correction evaluation.

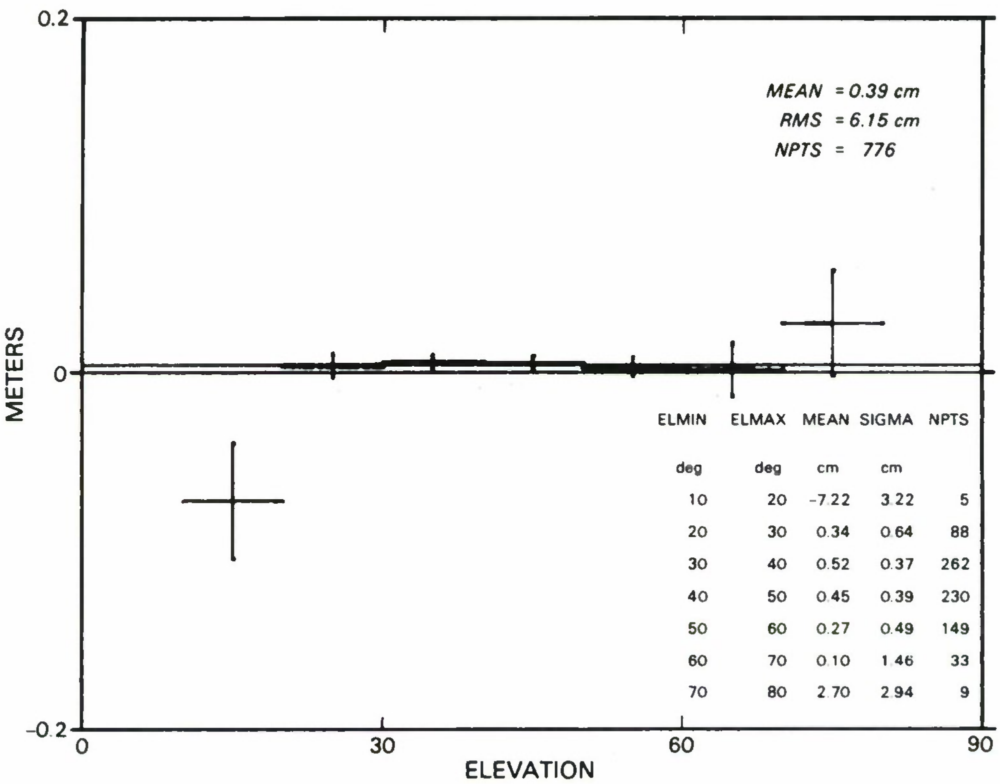

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Figure 8. Matera — MTLRS tropospheric correction evaluation.

VI. DISCUSSION

By any standard the results of this collocation inter-comparison are remarkable and the performance of the three satellite laser ranging systems is outstanding. That the overall agreement of the three systems is 1.7 cm is a tribute to the careful design and meticulous attention given to the details of the operation.

There were a number of false starts in the data reduction, evidenced by the number of "final" data releases. Nevertheless, the changes from iteration to iteration were generally small and so we have confidence that the sample of laser ranging data reported here can be considered typical. Thus, we feel justified in saying that the routine laser ranging available today has an absolute accuracy of 1 to 2 cm. This is also true for the Quick Look data, which are available shortly after each pass. Any near real-time uses of the data can be made with confidence.

The analysis of refraction models is also successful in the sense that we found no evidence of errors in the refraction model greater than 0.34. The data were limited to elevations greater than 20°, so the mapping function could not be tested with great sensitivity. The difficulty in mapping functions occurs below 10° elevation. Therefore, although we can say that there is no evidence for error in the mapping function above 20°, we are not in effect saying very much. However, the variation in the mapping function does allow a rather strong statement to be made about Zenith refraction. We believe that the Zenith refraction has errors smaller than 0.12 cm.

We must be cautious in using the calibration and refraction results as they are not independent in this analysis. The system calibration was investigated assuming the refraction model was correct, and vice versa. Nevertheless, the error bounds are comfortably small.

SUMMARY

In Summary we have come to the following conclusions:

(1) Normal point computation is an effective way to compress data.

(2) The three satellite laser ranging systems (Matera, MTLRS1, and MTLRS2) have systematic differences less than 1.7 cm.

(3) The Zenith refraction computed from the Marini and Murray troposphere model has an error less than 1.2 mm, and there is no evidence of error in the mapping function down to 20° elevation.

(4) The Quick Look data have no significant differences from the full rate data, and have an accuracy better than 1 to 2 cm.

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2. J.W. Marini and C.W. Murray, Jr., Goddard Space Flight Center, NASA-TM-X-70555 (1973).
3. E.M. Gaposchkin, "Metric Calibration of the Millstone Hill L-Band Radar," Technical Report 721, Lincoln Laboratory, MIT (19 August 1985), DTIC AD-A160362.
4. J.L. Davis, T.A. Herring, I.I. Shapiro, A.E.E. Rogers, and G. Elgered, Radio Sci. **20**, No. 6, 1593 (1985).
5. J. Saastamoinen, Third International Symposium on the Use of Artificial Satellites for Geodesy, Geophysical Monograph Series, Vol. 15, Henriksen et al, Eds. (American Geophysical Union, Washington D.C., (1972), p. 247.

APPENDIX A

WEGENER Quick-Look Format

The WEGENER quick-look format consists of one header line for each pass and data lines with up to three range and time paired observations per line. Also included in each pass is an indicator to identify the end of the pass. The first line of each quick-look transmission, regardless of the number of passes in that transmission is a number which represents the total number of range and time paired observations in the transmission. A sample pass is shown, followed by a character by character description of the format.

6	Line 1
790740010850401008505000204005000000075	Line 2
0122030021560072412152477001223500215100718942358940012259002154006804267339022 5	Line 3
012306002155006741388745600123150021540065883662424001232100215600614995223182 35	Line 4
END	

Line 1 Total number of range and time paired observations
in transmission. The number is left-justified.

Line 2 Pass Header

Character 1-6 — 4-digit marker number (7907=Arequipa, Peru) followed by 2-digit station number

7-8 — 2-digit satellite identifier

01=LAGEOS

02=Starlette

03=BE-3

04=EGP

9 — Always 0

10-15 — Date of first observation in pass in YYMMDD format

Year=85

Month=04

Day=01

16 — Always 0

17-21 — Atmospheric pressure, in tenths of millibars (850.5mb)

22 — Always 0

23-27 — Temperature, in tenths of degrees Celsius (20.4 degrees C)

Leading digit (Character 23) is sign digit

0=+

1=-

28 — Always 0

29-31 — % relative humidity (50%)

32 — Always 0

33-36 — Spare

37 — Always 0

38-40 — Checksum (075) Sum of all digits in the header line

Line 3 Data

Character 1-13 — Time of observation (see note 2)

Characters 1-6 are in HHMMSS format

Hour = 01

Minutes = 22

Second = 03

Characters 7-13 are tenths of microseconds

(.0021560 seconds)

14 — Always 0

15-25 — Range, in hundreds of centimeters
(72412152477=7241.2152477 kilometers)

26 — Always 0

27-39 — Time of next observation (same format as Characters 1-13)

40 — Always 0

41-51 — Range, paired with time in Characters 27-39
(same format as Characters 15-25)

52 — Always 0

53-65 — Time of next observation (same format as Characters 1-13)

66 — Always 0

67-77 — Range, paired with time in Characters 53-56 (same format as Characters 15-25)

78-80 — Checksum (225) Sum of all digits on this line

Line 4 is decoded in the same manner as line 3

Line 5 END — Appears at the end of each pass in transmission

NOTES:

(1) If meteorological values are zero in a pass, the refraction correction has already been applied. If applied, refraction is from Marini-Murray (1973).

(2) Epoch time of observation. See station table for time source. Most timing during the WEGENER-MEDLAS campaign will be referenced to UTC (USNO).

(3) 2.99792458×10^8 m/s will be used as the speed of light when computing ranges.

(4) All satellite ranges are from the intersection of the optical axes.

(5) Center of mass correction not applied.

(6) Laser wavelengths in station table.

(7) The number in Line 1 of the sample pass is the total number of time-range pairs in the transmission, not the number of lines in the transmission.

APPENDIX B

Merit Format For Laser Ranging Observations
A 90 Character Card Image Representation

I. Range

Column	Subset	Description
1-7		Satellite COSPAR ID
8-9		Measurement Type 20 = Laser range data
10-11		Epoch Time System Indicator
	10	Epoch Event 0 = Ground receive time 1 = Satellite transmit time 2 = Ground transmit time 3 = Satellite receive time
	11	Epoch Time Scale 0 = UTO 1 = UT1 2 = UT2 3 = UTC (USNO) 4 = A.1 (USNO) 5 = TAI 6 = A-S (Smithsonian) 7 = UTC (BIH) 8 = Unassigned 9 = Other
12-16		Station ID

Column	Subset	Description
17-32		GMT of Observation
	17-18	Year of Century
	19-21	Day of Year
	22-32	Time of Day (microseconds from midnight GMT)
33-35		Preprocessing Indicators
	33	Ionospheric Refraction Correction 0 = Data has been corrected 1 = Data has not been corrected
	34	Tropospheric Refraction Correction 0 = Data has been corrected, no meteorological data available 1 = Data has not been corrected, no meteorological data available 2 = Data has been corrected using international laser formula, no meteorological data available 3 = Data has not been corrected, Columns 76-80 contain coefficient for international laser formula 4 = Data has been corrected using the Marini-Murray formula, meteorological data available in Columns 57-66

Column	Subset	Description
	35	Transponder Delay Correction 0 = Data has been corrected 1 = Data has not been corrected
36-54		Observation Data
	36-54	Laser Range (Micrometers)
55-56		Preprocessing Indicators
	55	Normal Point Window Indicator 0 (or blank) = Range not a normal point 4 = 15-second normal point 5 = 30-second normal point 6 = 1-minute normal point 7 = 2-minute normal point 8 = 3-minute normal point
	56	See Columns 89-90
57-66		Meteorological Data
	57-60	Surface Pressure (millibars)
	61-63	Surface Temperature (degrees Kelvin)
	64-66	Relative Humidity at Surface (percent)
67-68		Crustal Dynamics Project: System Number
69-73		Measurement standard deviation (millimeters)

Column	Subset	Description
74-75		Crustal Dynamics Project: Occupancy Sequence Number
76-80		Tropospheric refraction correction (millimeters) or Coefficient of tropospheric refraction for international laser formula (millimeters)
81		Speed of Light Indicator 0 = 299792.5 km/s 1 = 299792.458 km/s
82		Center of Mass Correction Application Indicator 0 = Applied 1 = Not applied
83-88		Center of Mass Correction (millimeters)
89-90		If normal point range is used, then the digits in Columns 56, 89, 90 form the three-digit number of raw ranges compressed into the normal point (0 implies raw range). If format contains raw ranges, these columns may contain log 10 of the standard deviation of the time of observation (microseconds).

II. Azimuth /Elevation and X-Y Angles

Column	Subset	Description
1-7		Satellite COSPAR ID
8-9		Measurement Type 70 = Laser azimuth and elevation angles
10-11		Epoch Time System Indicator
	10	Epoch Event 0 = Ground receive time 1 = Satellite transmit time 2 = Ground transmit time 3 = Satellite receive time
	11	Epoch Time Scale 0 = UTO 1 = UT1 2 = UT2 3 = UTC (USNO) 4 = A.1 (USNO) 5 = TAI 6 = A-S (Smithsonian) 7 = UTC (BIH) 8 = Unassigned 9 = Other
12-16		Station ID
17-32		GMT of Observation

Column	Subset	Description
	17-18	Year of Century
	19-21	Day of Year
	22-32	Time of Day (microseconds from midnight GMT)
33-35		Preprocessing Indicators
	33	Ionospheric Refraction Correction 0 = Data has been corrected 1 = Data has not been corrected
	34	Tropospheric Refraction Correction 0 = Data has been corrected 1 = Data has not been corrected
35		Not used
36-54		Observation Data
	36-38	Azimuth or X-angle (degrees) (Sign of X-angle appears in Column 36)
	39-40	Azimuth or X-angle (arc minutes)
	41-45	Azimuth or X-angle (XX.XXX arc seconds)
	46	Sign of Y-angle
	47-48	Elevation or Y-angle (degrees)
	49-50	Elevation or Y-angle (arc minutes)
	51-54	Elevation or Y-angle (XX.XX arc seconds)
55-57		Not used
58-61		Standard deviation in X-angle or azimuth (XX.XX arc minutes)
62-65		Standard deviation in elevation or Y-angle (XX.XX arc minutes)

Column	Subset	Description
66		Preprocessing Report 0 = Report not indicated 1-9, A-Z Values to be assigned
67-71		Tropospheric Refraction Correction to X-angle (XXX.XX arc minutes)
72-76		Tropospheric Refraction Correction to Y-angle or elevation (XXX.XX arc minutes)
77-78		Crustal Dynamics Project: System Number
79-80		Crustal Dynamics Project: Occupancy Sequence Number
81-90		Not used

APPENDIX C

Millstone Hill "N" Format

The program DYNAMO accepts an input, metric data in the following format, in addition to the LL metric data base format. This format is a derivative of the NASA data format, modified for LL use.

Each data record has and "N" in column 1.

The data record is read with the FORTRAN input statement

```
   READ (LU,10) NSAT,MEASTY,ITSYS,NS IPREP,MJD,TF,ROB,SIG,TROP,CMASS
10 FORMAT (1X,16,213,15,112,16,F12.10,F12.2,3F6.2)
```

NSAT : Six digit satellite number.

MEASTY : Measurement type

6 = range (meters)

26 = SST range (meters)

36 = SST range rate (meters/second)

IYSYS : Time system in the form (N*10+M)

N=0 Ground receive time

N=1 Time at satellite

N=2 Ground transmit time

M=0 UT0 (not implemented)

M=1 UT1 (not implemented)

M=2 UT2 (not implemented)

M=3 UTC

M=4 A1 (not implemented)

NS : Station number (5 digits)

For SST data, the second satellite number.

IPREP : Preprocessing code.

Bit(s)	Octal	Decimal		Meaning
5-6	600000000(8)	100663296(10)	.NE.3	old value of speed of light.
12	2000000(8)	524288(10)	.EQ.0	has been corrected for refraction.
			.EQ.1	has not been corrected for ref.

13	1000000(8)	262144(10)	.EQ.0	refraction correction given in TROP.
			.EQ.1	Zenith value given in TROP.
14	400000(8)	131072(10)	.EQ.0	corrected for center of mass.

Simulated observations could have IPREP=100663296(10), which indicates, all corrections are applied, and the modern speed light is used.

The IPREP codes control application of corrections, i.e. if refraction and center of mass corrections are given, they are not applied unless the appropriate codes are set.

MJD	: Modified Julian Date of Observation.
TF	: Fractional part of date (days).
ROB	: Observed quantity, (meters, meters/sec).
SIG	: Uncertainty of observation (meters, meters/sec).
TROP	: Refraction correction, if needed, (meters).
CMASS	: Correction for center of mass (meters).

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

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Three laser ranging stations were collocated at Matera, Italy, in January, February, and March 1986. They observed 92 passes of the LAGEOS Satellite, of which 56 passes were observed by more than one system. This set of data allows intercomparison of the three laser ranging systems, and assessment of the Quick Look data from each system. In addition, this data set allows examination of tropospheric refraction models using dispersion since two distinct optical wavelengths were used. It has been found that the three laser ranging systems agree to within 1.7 cm in range. It has also been found that the nominal (Marini and Murray, 1973) refraction model has no significant errors greater than 0.12 cm in Zenith refraction and 0.64 cm in the mapping function down to 20° elevation.

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